VII International Conference on Computational Methods in Marine Engineering
MARINE 2017
M. Visonneau, P. Queutey and D. Le Touzé (Eds)

MODELLING OF HYDRODYNAMIC LOADS ON AQUACULTURE NET CAGES BY A MODIFIED MORISON MODEL

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Key words: Hydrodynamic load models, Aquaculture structures, Net cages

Abstract. A modified Morison model is presented for calculation of hydrodynamic forces on aquaculture net cages. The model is based on a simple method for conversion of *"screen model force coefficients"* to approximate equivalent directional dependent *Morison coefficients*. The motivation for this is that experimentally obtained force coefficients for net panels are generally presented as screen model force coefficients, while commercial analysis software are often restricted to a Morison model. Based on the screen model force coefficients defined by *Løland's formulas*, the method is implemented in the nonlinear finite element program USFOS. Analyses with the modified Morison model are performed, investigating the viscous forces on a net panel for different inflow angles. The numerical results are benchmarked against Løland's original screen model, showing good agreement for all inflow angles. Comparison with the classical Morison model is made to illustrate the advantage of the proposed method. The model is also applied for calculation of hydrodynamic forces on the net of a real aquaculture structure exposed to a steady current. Again, the results are compared to Løland's original screen model, showing an almost exact reproduction of the global drag force.

1 INTRODUCTION

Proper hydrodynamic modelling is extremely important in order to accurately estimate the response of a structure exposed to the marine environment. For aquaculture strucutures, this is a challenging task. Typical fish farms represents a highly elastic system where fluid-structure interaction effects are important. Calculation of the forces by state-of-the-art computational fluid dynamics (CFD) methods are prohibitively expensive since the number of twines for a fish farm net is in the order of ten millions, calling for rational methods for assessment of the hydrodynamic loads on aquaculture net cages [1].

Generally, two different types of hydrodynamic models are applied for calculation of viscous forces on nets or screens: (1) Morison type and (2) screen models. The advantage of approach (1) lies in its simplicity and widespread use for analysis of slender marine structures – literally all relevant analysis tools include the option to select such a hydrodynamic model. On the downside, it largely over-predicts the drag force for large inflow angles on a net panel as it is not able to capture important fluid-structure interaction effects, which typically are dependent on the inflow angle. In addition, a drag model based on the cross-flow principle cannot be justified for inflow angles larger than about 45 degrees [1]. Application of Morison models for calculation of hydrodynamic forces on aquaculture net cages are found in e.g. Tsukrov et al. [2], Fredriksson et al. [3], Moe et al. [4, 5], Fredheim [6] and Zhao et al. [7]. Bi et al. [8] used it in combination with a porous media fluid model to also simulate the effect the presence of the net cage has on the flow.

In approach (2), the net is divided into several net panels/screens, and the hydrodynamic force is decomposed into a drag and a lift component. By defining the unit normal vector of the net panel, it is possible to take into account the angle between the incoming flow and the net panel, resulting in more accurate force estimation. Another advantage is that experimentally obtained force coefficients for net panels are typically presented as *"screen model force coefficients"* [9, 10, 11, 12]. The main drawback is that screen models are often not available in commercial analysis software. Presentation and application of screen models for calcualtion of hydrodynamic forces on net cages are found in e.g. Løland [9], Kristiansen and Faltinsen [1, 13], Huang et al. [14] and Lader and Fredheim [15].

In this paper, a modified Morison model will be presented for calculation of hydrodynamic loads on aquaculture net cages. The model is based on a simple method for converting screen model force coefficients to approximate equivalent *directional dependent* Morison coefficients. The motivation for this is that experimentally obtained force coefficients for net panels are generally presented as screen model force coefficients, while most analysis tools are restricted to a Morison type hydrodynamic force model. The method allows for direct application of experimentally obtained screen model force coefficients in a Morison model, including the force dependence on the inflow angle relative to the net panel.

2 HYDRODYNAMIC MODEL

In the following, the proposed hydrodynamic model will be described. For convenience, we will first outline the basic principles behind both the classical Morison type models and the screen models.

2.1 The Morison model

For calculation of hydrodynamic loads on slender marine structures, Morison's equation [16] is frequently used. It gives us the *cross-flow force* on a member based on the cross-flow principle [1]. In the case of a fixed structure, the total hydrodynamic force is split into an inertia term, representing the Froude-Krylov force and the diffraction force, and a drag term, representing the viscous drag forces. It is assumed that the water particle velocity and acceleration in the region of the structure do not differ significantly from the value at the cylinder axis; an assumption generally valid for $D/\lambda < 0.2$, where D is the structural diameter and λ is the wave length [17]. For a vertical rigid circular cylinder, the classical Morison's equation tells us that the total force normal to the cylinder axis, i.e. the horizontal force, dF on a strip of length dz can be written as [18]:

$$dF = \rho \frac{\pi D^2}{4} dz C_m \cdot a_1 + \frac{1}{2} \rho C_d D dz \cdot u \mid u \mid \tag{1}$$

where ρ is the water density, D is the diameter of the cylinder, C_m and C_d are the inertia and drag coefficients, respectively, and a_1 and u are, respectively, the horizontal water particle acceleration and velocity.

If the structure moves, the acceleration of the structure must be accounted for in the added mass part of the inertia term, and the velocity of the structure in the drag term. The general expression for the total force per unit length normal to the axis of the considered structural member can then be written as [17]:

$$F_n = \rho C_m dV \cdot a_n - \rho(C_m - 1) dV \cdot \ddot{\eta}_n + \frac{1}{2} \rho C_d dA \cdot (u_n - \dot{\eta}_n) \mid u_n - \dot{\eta}_n \mid \tag{2}$$

here, u_n and a_n are, respectively, the wave particle velocity and acceleration perpendicular to the member, $\ddot{\eta}_n$ and $\dot{\eta}_n$ are the time derivatives of the member motion perpendicular to the member and dA and dV are the exposed area and displaced water per unit length.

Even though it is not considered in the original Morison's equation, the presence of a mean lift force can be handled by introducing

$$\bar{F_l} = \frac{1}{2} \rho C_l dA \cdot u_n^2 \tag{3}$$

where, $\bar{F_l}$ is the mean lift force, which is orthogonal to u_n in the cross-flow plane, and C_l is the lift coefficient. $\bar{F_l}$ is zero for a single body in infinite fluid when the body is symmetric about the axis parallel to the direction of u_n [18]. The mean lift force is therefore seldom considered for slender marine structures as they typically have circular cross-sections. The motion of the structure can be handled by replacing u_n in Eqn. (3) with the relative normal velocity.

An illustration of the different force contributions acting on a structural member is shown in Fig. 1 , where f_N corresponds to the force predicted by Morison's equation. The tangential force f_T, which is primarily due to shear forces (skin friction), is generally negligibly small for net threads [1].

A simple example, illustrating the use of a Morison type force model for calculation of the cross-flow forces on a net exposed to a steady current, is shown in Fig. 2. The mean lift force on

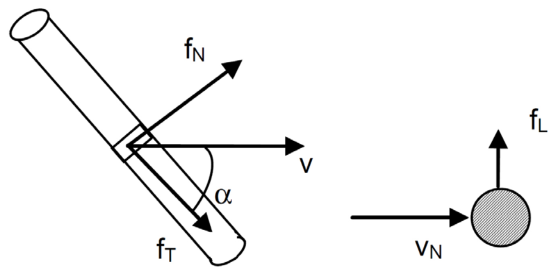
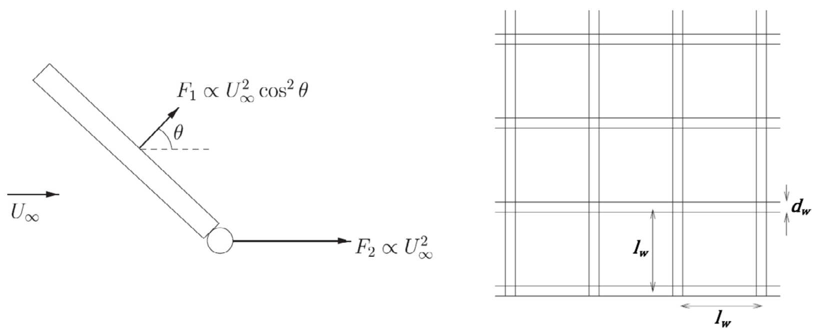


Figure 1: Definition of normal force f_N, tangential force f_T and lift force f_L on an inclined slender structural member exposed to a water particle velocity V. Illustration from [19].

element level is not considered. Note that even though only the drag term of Morison's equation contribute to the two element forces F_1 and F_2, the drag force on the inclined cylinder (F_1) is actually contributing to a lift force on the net seen from a global perspective.



(a) (b)

Figure 2: **(a)** Illustration of a Morison type force model applied to two twines in a steady current of magnitude U_∞. **(b)** Illustration of a net with twine diameter d_w and twine length l_w. Illustrations from [1].

2.2 The screen model

The basic assumption in screen models is that the net cage can be divided into several *net panels*, or *screens*, and the model aims to provide a good estimate of the total force acting on each of these net panels. The screen models are primarily made for analysis of net cages in current, but due to a quasi-static assumption ($KC \gg 1$), they are also applicable in waves [1].

The mean drag and lift force on a net panel/screen are typically dependent on force coefficients which magnitude depends on (among other things) the inflow direction relative to the screen. They can be written as:

$$F_{d,screen} = \frac{1}{2}\rho C_{d,screen}(\theta)A' \cdot U_{rel}^2 \tag{4}$$

$$F_{l,screen} = \frac{1}{2}\rho C_{l,screen}(\theta)A' \cdot U_{rel}^2 \tag{5}$$

where,

$F_{d,screen}$	force on the net panel in direction of the local (relative) inflow.
$C_{d,screen}$	drag coefficient of the screen.
$F_{l,screen}$	force on the net panel perpendicular to the local (relative) inflow.
$C_{l,screen}$	lift coefficient of the screen.
A'	area of the net panel.
U_{rel}	relative inflow velocity.
ρ	density of water.
θ	angle between the relative inflow direction and the net normal vector in the direction of the flow.

The panels are characterized by their solidity ratio Sn and their orientation relative to the (relative) inflow, denoted by the angle θ [1]. The solidity ratio is the ratio of the area projected by the threads of a screen to the total area of the net panel. The definition of the angle θ is illustrated in Fig. 3, together with the unit normal vector $\mathbf{n}$ and the relative inflow unit vector $\hat{\mathbf{u}}$. The direction of the drag on a panel is defined in the direction of the relative inflow unit vector $\hat{\mathbf{u}}$. The lift direction is perpendicular to $\hat{\mathbf{u}}$, and is defined by the cut between the plane defined by $\mathbf{n}$ and $\hat{\mathbf{u}}$, and the normal plane of $\hat{\mathbf{u}}$. Mathematically, the lift unit vector $\mathbf{l}$ can be expressed as:

$$\mathbf{l} = \frac{\hat{\mathbf{u}} \times (\hat{\mathbf{n}} \times \hat{\mathbf{u}})}{\mid \hat{\mathbf{u}} \times (\hat{\mathbf{n}} \times \hat{\mathbf{u}}) \mid} \tag{6}$$

where $\hat{\mathbf{n}}$ is the unit normal vector of the panel defined such that it always point into the same half-space as the relative flow velocity, i.e.:

$$\hat{\mathbf{n}} = \mathrm{sign}\left(\mathbf{n} \cdot \hat{\mathbf{u}}\right)\mathbf{n} \tag{7}$$

The reason why the total force on a net panel is not in the inflow direction, is due to deflection of the flow through the screen [1].

The drag and lift coefficients, $C_{d,screen}$ and $C_{l,screen}$, are primarily determined based on experiments with net panels in steady flow. The most important parameters, governing the magnitude of these coefficients, are found to be the solidity ratio Sn and the inflow angle θ [9]. Løland [9] and Aarsnes et al. [20] have developed analytical formulas for the drag and lift coefficients of screens as functions of the mentioned parameters. The model presented by Kristansen and Faltinsen [1], also takes into account the Reynolds number.

The screen models consider the viscous drag and lift forces on the net panels. Inertia forces can be included in a similar manner as in the Morison models, see e.g. [14]. Even though viscous forces dominate, experiments with net panels exposed to waves have concluded that inertial forces on net structures are significant [21]. However, few results on the magnitude of the inertia coefficients exist, and typical values for circular cylinders are thus generally applied.

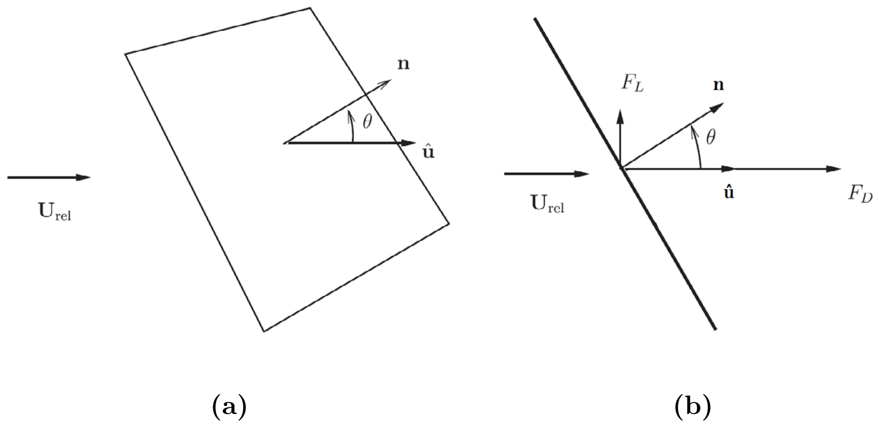


Figure 3: **(a)** Net panel of arbitrary orientation. Indicated are the net unit normal vector $\mathbf{n}$, the relative inflow unit vector $\hat{\mathbf{u}}$ and the angle between these vectors θ. **(b)** Two-dimensional net panel. F_D is the drag force and F_L is the lift force. Illustrations from [1].

2.3 Proposed hydrodynamic model

2.3.1 Note on the structural model

The net consists of millions of individual threads and twines [1]. Direct modelling thus involves a huge number of elements. This is not feasible for a structural analysis due to the enormous computational time and resources such a model would have required. A simplified model of the net with a coarser mesh must therefore be applied to keep the computational time within reason. The elements of this coarse mesh are modelled as circular cylinders, which are assigned an *equivalent* cross-sectional area, adding up the areas of the individual threads each element represents, so that the cross-sectional area is conserved. It is important to realize that such a procedure does not conserve the exposed area found in the drag term of Morison's equation (see Eqn. (2)), meaning that the modelled net will have a smaller solidity ratio than the physical net. In the examples of the proposed hydrodynamic model, the elements have been modelled by three-dimensional beam elements. The reason for this choice is that the applied analysis software is optimized for such elements. The method is however equally applicable for truss and spring elements, which are more commonly used for netting structures.

2.3.2 The modified Morison model

The screen models gives us global directional dependent drag and lift coefficients for a whole net panel in accordance with Eqn. (4) and (5). If these are to be applied in a Morison model, the *screen model* drag and lift coefficients must be converted into *equivalent* Morison coefficients on element level, giving the same *total force* on the net panel. This is not a straight forward procedure as Morison's equation uses the relative water particle velocity *normal* to the members in addition the *element* area, while the screen model uses the relative velocity and the *net panel* area. The lift and drag *directions* are also somewhat differently defined, and it is not common that the Morison coefficients are functions of the inflow angle, as is the case for the screen model coefficients. A simple method to convert *screen model force coefficients* to be used in a modified Morison model, applying directional dependent coefficients, has thus been made. The idea behind the method can be explained by a simple example.

Consider the physical, plane net in Fig. 2b exposed to a steady current of magnitude U_∞. Denote the area of this net panel as A'. In an assumed structural model, this net panel is simply modelled by two elements; one vertical with a projected area A_V, representing the vertical threads, and one horizontal with projected area A_H, representing the horizontal threads, i.e. similar as in Fig. 2a (the length of the horizontal member is in the direction normal to the paper plane in this figure). In a screen model, the drag forces on the net is now determined by the *physical* properties of the net, the flow characteristics and the screen model drag coefficient $C_{d,screen}$, in accordance with Eqn. (4). We now want to obtain *equivalent* drag coefficients to be used in a Morison model, giving the same total force on the net. If the current is normal to the net panel, the only difference between the Morison and the screen model is the area which the force coefficients are normalized by. The equivalent Morison drag coefficient C_d, is then simply obtained as:

$$C_d = \frac{C_{d,screen}}{Sn_{model}}, \quad \text{where } Sn_{model} = \frac{A_H + A_V}{A'} \tag{8}$$

Now, the net panel is given an angle θ relative to the current, as illustrated in Fig. 2a. The drag on the vertical member is then reduced by a factor of $\cos^2\theta$. Defining the *element normal vector* in the same direction as the normal vector of the net panel, it is noted that the current now arrives at an angle corresponding to a cross-sectional angle $\phi = \theta$ on the horizontal member relative to the element normal vector (see Fig. 4a for an illustration of ϕ). To compensate for the force reduction on the vertical member, we want to modify the drag coefficient of the horizontal member in such a way that the total obtained force is compatible with the screen model. This means that we have to solve the following equation with respect to the drag coefficient of the horizontal member, $C_{d,H}$:

$$\frac{1}{2}\rho C_{d,screen}(\phi)\, A' U_\infty^2 = \frac{1}{2}\rho C_{d,H}(\phi)\, A_H U_\infty^2 + \frac{1}{2}\rho C_{d,V} A_V U_\infty^2 \cos^2\theta$$

Noting that $A' = \frac{A_H + A_V}{Sn_{model}}$ and introducing the crude approximation that the drag coefficient of the vertical element $C_{d,V} = \frac{C_{d,screen}(\phi)}{Sn_{model}}$, as in Eqn. (8), the following result is obtained:

$$C_{d,H}(\phi) = \frac{C_{d,screen}(\phi)}{Sn_{model}} \left(1 + \frac{A_V}{A_H}\sin^2\phi\right) \tag{9}$$

The latter term in Eqn. (9) can be thought of as a directional-dependent *correction factor*.

In the three-dimensional case, the inflow can also arrive at an cross-sectional angle on the vertical member relative to the element normal vector. This is accounted for in a similar way as in Eqn. (9), and the drag coefficient of the vertical member $C_{d,V}$, can be expressed as:

$$C_{d,V}(\phi) = \frac{C_{d,screen}(\phi)}{Sn_{model}} \left(1 + \frac{A_H}{A_V}\sin^2\phi\right) \tag{10}$$

This approach is exact for inflow normal to the net panel and parallel to the net panel. For intermediate inflow angles, it is only an approximation. The model will slightly overpredict

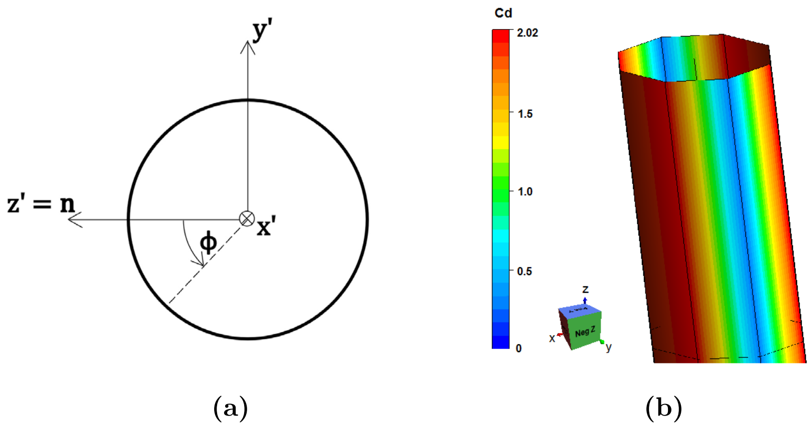


Figure 4: **(a)** Definition of the cross-sectional angle ϕ in the element local coordinate system. The local Z-axis is defined in the direction of the element normal vector $\mathbf{n}$ (the net panel plane is thus in the local XY-plane). **(b)** Visualization of a circular cylinder with a direction dependent drag coefficient as applied in section 3.1.

the drag forces normal to the net panel, and underpredict the forces parallel to the net panel compared to a screen model.

We now introduce lift coefficients on element level, following Eqn. (3). The magnitude of these coefficients are determined based on the screen model lift coefficients, and are both for the vertical and horizontal member, simply expressed as:

$$C_l(\phi) = \frac{C_{l,screen}(\phi)}{Sn_{model}} \tag{11}$$

As the drag term in Morison's equation already has contributed to a lift force (see Fig. 2a), the directional-dependent correction factor is not included in Eqn. (11). This is seen to improve the overall performance of the model, counteracting the over- and underprediction mentioned above. Note that the magnitude of the lift coefficients of a net panel are much less than the drag coefficients.

The procedure for implementing the modified Morison model on a whole net cage is given below.

1. Define an *element unit normal vector* $\mathbf{n}$ in the same direction as the *local net panel normal vector* for all net elements. One of the *principal axes* of each element's local coordinate system must then be defined in the direction of its *element normal vector* to ensure a consistent definition of the element cross-sectional angle ϕ (see Fig. 4a).

2. Estimate directional dependent *screen model force coefficients* for the *physical* net based on empirical formulas such as Løland's formulas [9], model tests or other methods giving coefficients on the format of Eqn. (4) and (5). The *physical* properties of the net should be used here (not the modelled). As the net will serve as a surface for biofouling [22], a larger solidity than the *clean net solidity* should be applied in design calculations.

3. Calculate the local solidity ratio Sn_{model}, and the local area ratios $\frac{A_H}{A_V}$ and $\frac{A_V}{A_H}$ for the *modelled* net. Depending on the modelling strategy, one might get different values of Sn_{model} and the area ratios for different parts of the net. Uniform meshing is recommended to simplify this step.

4. Convert the *screen model force coefficients* to approximate equivalent directional dependent *Morison coefficients* on element level as:

$$C_{d,V}(\phi) = \frac{C_{d,screen}(\phi)\left(1 + \frac{A_H}{A_V}\sin^2\phi\right)}{Sn_{model}} \tag{12}$$

$$C_{d,H}(\phi) = \frac{C_{d,screen}(\phi)\left(1 + \frac{A_V}{A_H}\sin^2\phi\right)}{Sn_{model}} \tag{13}$$

$$C_l(\phi) = \frac{C_{l,screen}(\phi)}{Sn_{model}} \tag{14}$$

where,

$C_{d,V}$	element drag coefficient of vertical net elements.
$C_{d,H}$	element drag coefficient of horizontal net elements.
C_l	element lift coefficient of both vertical and horizontal net elements.
A_V	local modelled exposed area of the vertical net elements.
A_H	local modelled exposed area of the horizontal net elements.
ϕ	element cross-sectional angle (see Fig. 4a).

5. The inertia forces are included as in a regular Morison model. In lack of experimental data, standard values for the inertia coefficient of circular cylinders could be applied, e.g. $C_m = 2$. The effect of biofouling should be accounted for in design calculations.

6. When the net cage is exposed to a current, the shielding effect from the net panels upstream, will lead to a *reduced* incident *current* velocity on the net panels and other structural components *downstream*. This should be accounted for. Løland [9] has suggested the following formula for this current velocity reduction factor r, which should be assigned to the downstream members:

$$r = \frac{u}{U_\infty} = 1.0 - 0.46C_{d,screen} \tag{15}$$

The derived drag, lift and inertia coefficients are now input to a modified Morison model, allowing both directional dependent coefficients and inclusion of the lift coefficient. The applied Morison model must be able to account for the motion of the structure. To properly account for hydroelasticity, the element local coordinate system must "follow" the displacements and rotations of each element. An illustration of an element with a directional dependent drag coefficient is shown in Fig. 4b.

2.3.3 Comments

As previously mentioned, the proposed conversion method is exact for inflow normal to the net panel and parallel to the net panel. For intermediate inflow angles, it is only approximate. The main approximation is related to the fact that the obtained force coefficients are directional dependent on the considered elements cross-sectional angle, only. Denoting the cross-sectional inflow angle on a vertical member as ϕ_V and the inflow cross-sectional angle on a neighbouring horizontal element as ϕ_H, exact conversion of the screen model coefficients would require the element force coefficient to by functions of both ϕ_V and ϕ_H. Such an approach would however require that the force coefficients are re-calculated at every time step, making it a complex and less attractive solution.

It is recommended to model the net by a rectangular mesh with an aspect ratio close to one (i.e. the ratio $\frac{A_V}{A_H}$ should not be too high or too low). The main reason for this is that very high aspect ratios of the mesh is somewhat problematic for the conversion of the lift coefficients. In addition, real nets typically have close to square meshes. A trapezoidal mesh could be applied for the bottom net as long as it does not deviate too much from a square shape.

The proposed modified Morison model requires the local modelled solidity ratio Sn_{model} and the local area ratio $\frac{A_V}{A_H}$ (and its inverse) for conversion of the screen model force coefficients. The implementation of the model becomes a lot easier if the local values of Sn_{model} and $\frac{A_V}{A_H}$ are varied as little as possible for the different part of the net, i.e. application of uniform meshing. For the side net, uniform meshing is easily performed. For the bottom net, this could be more challenging, but one should keep in mind that the forces on the bottom net are generally small compared to those on the side net. As long as the mesh size and aspect ratio of the modelled bottom net are not varied too much, *average values* could be used. Representation of the vertical net element on the side net with lengths exponentially increasing with depth (shorter lengths near the sea surface to better resolve the wave kinematics), will complicate the implementation. Numerical investigations by Kristiansen and Faltinsen [13] have, however, concluded that the difference in the obtained forces on net cages in waves by using uniform vertical meshing is negligibly small compared to using exponential vertical meshing.

A last comment is related to the implementation of the directional dependent lift coefficient, $C_l(\phi)$. Depending on how the element lift direction is defined in the applied analysis software, one must assure that the lift force is actually calculated in the correct direction. Typically, one has to change the sign of $C_l(\phi)$ for every 90° of ϕ.

3 RESULTS – VALIDATION OF THE MODEL

The presented modified Morison model has been implemented in the nonlinear finite element program USFOS [23]. The drag and lift coefficients are based on screen model force coefficients found by application of Lølands formulas [9], i.e.:

$$C_{d,screen}(\theta) = 0.04 + (-0.04 + 0.33Sn + 6.54Sn^2 - 4.88Sn^3)\cos\theta \tag{16}$$

$$C_{l,screen}(\theta) = (-0.05Sn + 2.3Sn^2 - 1.76Sn^3)\sin 2\theta \tag{17}$$

The above formulas are valid for nets with a solidity ratio in the range of 0.13 – 0.31.

Two examples will be given to demonstrate the performance of the model. In the first one, the viscous forces on a fixed net panel for different inflow angles will be investigated. In the second, the method will be applied for calculation of the viscous forces on a real aquaculture structure exposed to a steady current.

3.1 Viscous forces on a rigid net panel

A net panel of dimensions 1.0 m × 1.0 m was modelled in USFOS. The net is characterized by a solidity ratio $Sn = 0.15$, and is attached to rigid frame as shown in Fig. 5a. This is similar to the set-up typically applied for experimental determination of screen model force coefficients. The frame was modelled so that it only provided stiffness, but did not attract hydrodynamic loads.

The aim is to investigate the viscous forces on the net panel by application of the modified Morison model for different inflow angles. The drag and lift coefficients in the modified Morison model are based on Løland's formulas given by Eqn. (16) and (17), and converted according to Eqn. (12), (13) and (14). The drag coefficient of a net element is shown in Fig. 4b.

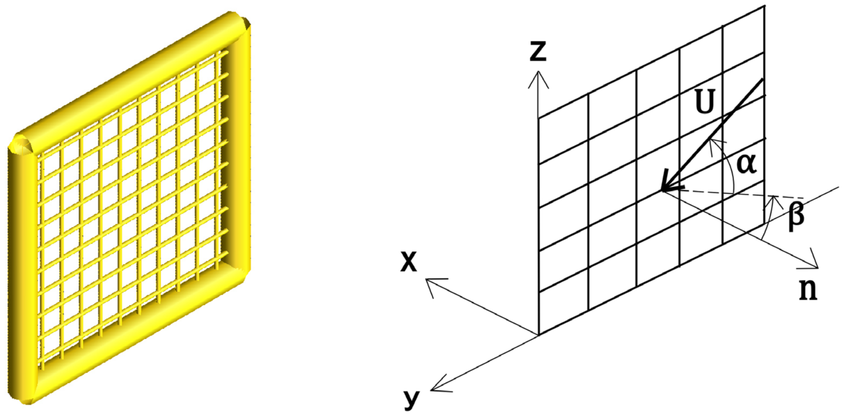
The properties of the net panel are given in Tab. 1. The solidity of the modelled net is taken equal at the solidity of the "real" net, i.e. $Sn_{model} = Sn$. A square, uniform mesh with $N_H \times N_V = 10 \times 10$, where N_H is the number of horizontal threads and N_V is the number of vertical threads, is applied.

In the numerical simulations, the net panel is exposed to an inflow velocity $\mathbf{U}$ of magnitude 1 m/s. The direction of $\mathbf{U}$ is given by the angles β and α, which are defined in Fig. 5b together with the global coordinate system. The net panel plane is in the global YZ-plane and the net panel normal vector $\mathbf{n}$ is defined in the negative X-direction. The angle β is the inflow angle in the XY-plane, and corresponds to the heading of a wave or a current relative to the net panel normal vector $\mathbf{n}$. The angle α is equivalent to the phase angle of the water particles in a long, regular, deep water wave with a heading defined by β. Inertia forces are not considered, and the analyses were run as quasi-static.

Table 1: Properties of the net and inflow used in the analyses.

Net panel properties				Inflow properties	
Sn	A	$D_{threads}$	Mesh	ρ	$\mid \mathbf{U}(\beta, \alpha) \mid$
0.15	1.0 m^2	15 mm	square 10×10	1024 kg/m^3	1.0 m/s

Analyses with four different inflows, each with a constant β angle, were run. These corresponds to β angles of 0°, 30°, 60° and 90°. The forces have been recorded over one wave period, i.e. all 360° of α, for each β value. $\beta = \alpha = 0°$ corresponds to inflow in the positive X-direction, normal to the net panel. The results obtained for the modified Morison model were bechmarked against Løland's original screen model. In addition, the results were compared to the classical Morison model. In the original screen model, the angle between the net panel normal vector and the incoming velocity vector, θ, is defined as $\theta = \cos^{-1}(\cos\alpha \cos\beta)$. In the classic Morison model, $C_d = 1.15$ has been applied, following [4]. The forces have been decomposed into their X-, Y- and Z-component, and are presented in Fig. 6, 7 and 8, respectively. To better illustrate



(a) **(b)**

Figure 5: **(a)** Net panel with dimensions 1x1 metres as modelled in USFOS. **(b)** Definition of the global coordinate system, the net normal vector **n** and the incoming water particle velocity **U** with inflow angles β and α. β is the inflow angle in the XY-plane, and corresponds to the heading of a wave/current relative to **n**, while α corresponds to the phase angle of a long, regular deep water wave with heading defined by β.

each force components relative importance, the force range on the vertical axis of the plots is kept constant for each β value.

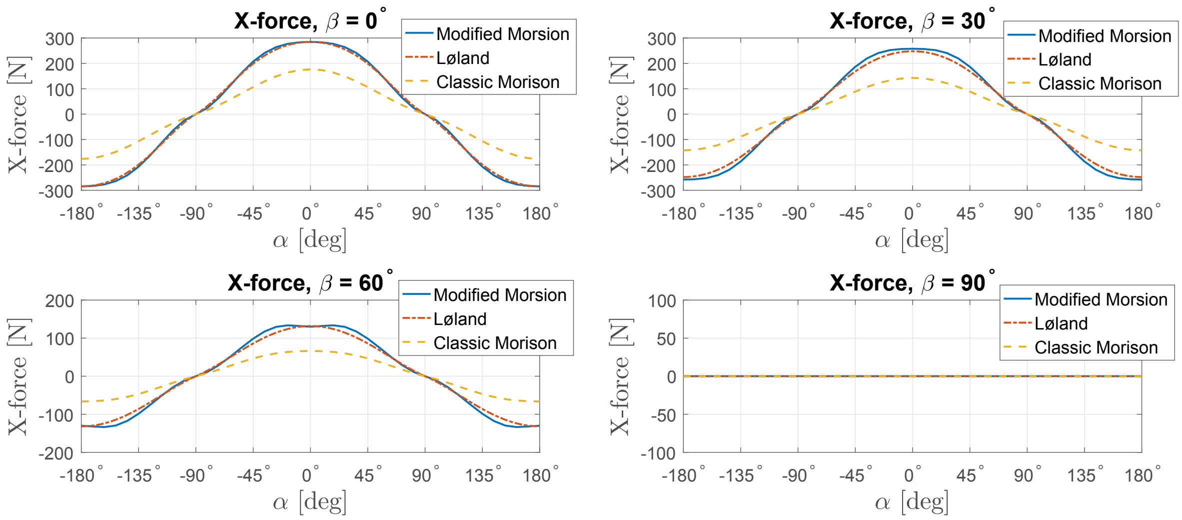


Figure 6: Comparison of the forces in X-direction. The angles α and β are defined in Fig. 5b.

As seen from the plots in Fig. 6, 7 and 8, the performance of the proposed Morison model is good, and it is able to accurately recreate the Løland screen model forces. Generally, the model slightly overpredicts the forces normal to the net panel (x-direction), with a correspondingly small underprediction of the forces parallel to the net panel (y- and z-direction). The classical

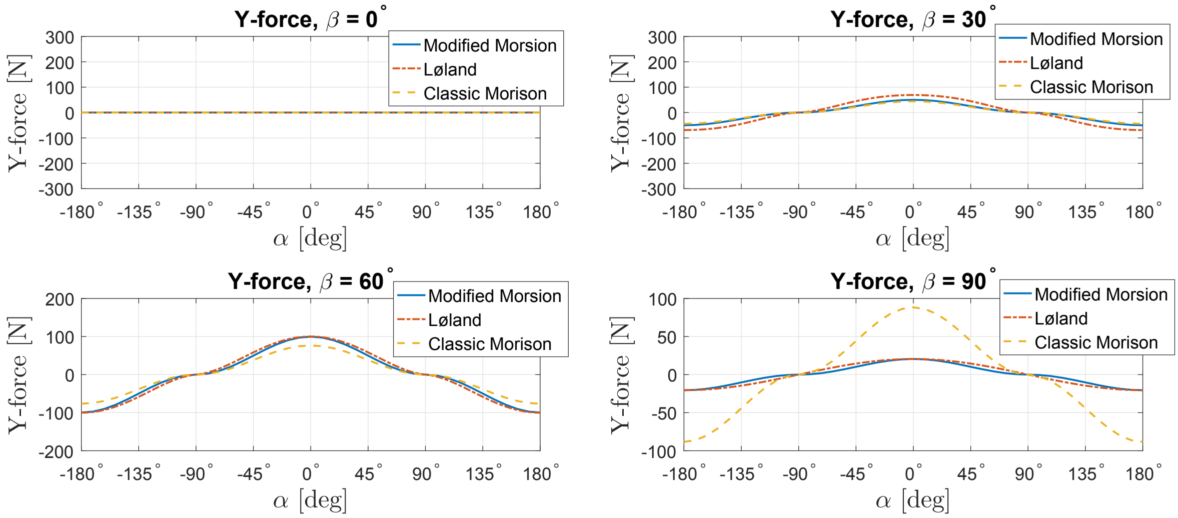


Figure 7: Comparison of the forces in Y-direction. The angles α and β are defined in Fig. 5b.

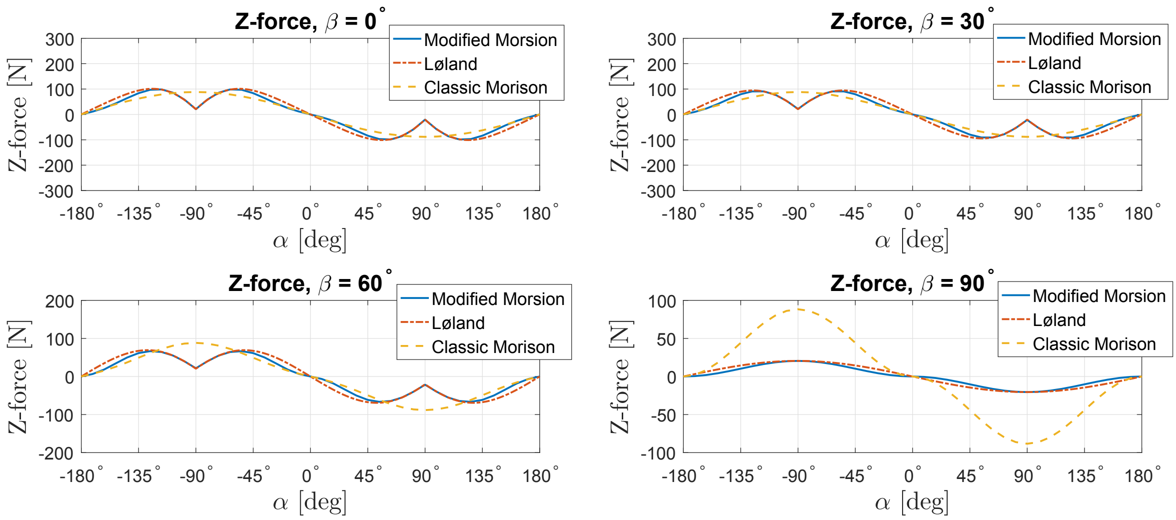
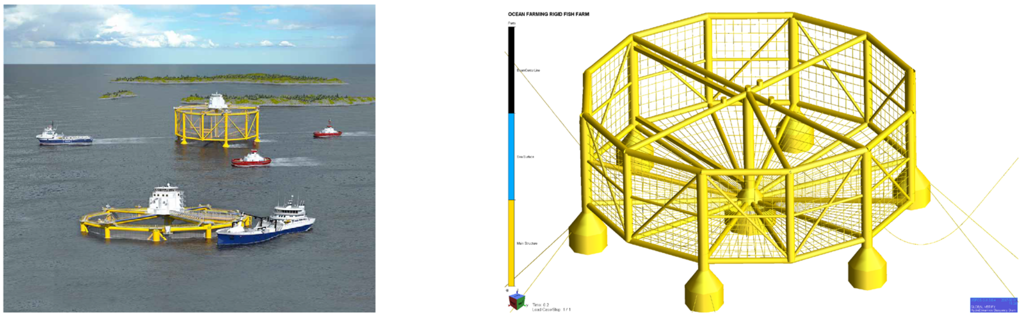


Figure 8: Comparison of the forces in Z-direction. The angles α and β are defined in Fig. 5b.

Morison model results are primarily included to illustrate the differences between the models. For this model, the overprediction of forces for inflow parallel to the net panel (i.e. for $\beta = 90°$ and all Z-forces with $\alpha = \pm 90°$) are clearly observed. Underprediction of the forces normal to the net panel compared to the screen model are also seen in Fig. 6.

3.2 Viscous forces on a rigid aquaculture structure in current

A rigid, semi-submersible aquaculture structure was modelled in USFOS, applying the modified Morison model as the hydrodynamic model for the net. Specifically, the considered structure is SalMar/Ocean Farming's concept *"Ocean Farm 1"*, illustrated in Fig. 9.



(a) **(b)**

Figure 9: **(a)** Illustration of the Ocean Farming concept. **(b)** The Ocean Farming concept as modelled in USFOS.

The side net is modelled by a uniform, approximately square mesh. The bottom net is modelled by a trapezoidal mesh which is not uniform. Related to calculation of the hydrodynamic coefficients, the bottom net has been split in two zones; one inner and one outer, separated at half the radius of the cage. Average values of Sn_{model}, $\frac{A_H}{A_V}$ and $\frac{A_V}{A_H}$ are used within each zone.

The hydrodynamic coefficients of the net elements are calculated based on Løland's formulas, Eqn. (16) and (17), and converted by Eqn. (12), (13) and (14). The shielding effect from the upstream net panels, causing a reduced incident current velocity on all downstream elements, is taken into account using Eqn. (15).

A simple validation of the global performance of the modified Morison model is made by exposing the structure to a steady current of magnitude $U = 0.75$ m/s. The total in-line hydrodynamic force acting on the *netting structure* is then computed. This is compared with calculations of the total in-line hydrodynamic force, using Løland's screen model directly. The results are found in Tab. 2.

Table 2: The total in-line hydrodynamic force acting on the netting structure of the Ocean Farming concept when exposed to a current of magnitude 0.75 m/s.

Modified Morison model	Løland
742 [kN]	748 [kN]

The agreement between the total force predicted by the modified Morison model and that by Løland's screen model is good. This suggests that the global performance of the modified Morison model is satisfactory.

4 CONCLUSIONS

A modified Morison model has been proposed for calculation of hydrodynamic forces on netting structures. The model is based on an introduction of directional dependent drag and lift coefficients. The magnitude of the coefficients, is determined by screen model force coefficients. By a simple method, these are then converted to equivalent Morison coefficients, giving approximately the same total force on a net panel as a screen model. This allows for direct application of screen model force coefficients in software restricted to a Morison type hydrodynamic model.

Based on the screen model force coefficients defined by Løland's formulas, the model was implemented in the nonlinear finite element program USFOS. Analyses with the modified Morison model were performed, investigating the viscous forces on a net panel for different inflow angles. The results were benchmarked against Løland's original screen model, showing good agreement for all inflow angles. Comparison with the classical Morison model was also made, illustrating the advantage of the proposed method. A validation of the global performance of the model on a real aquaculture structure was also made, comparing the obtained in-line hydrodynamic forces on the netting structure with Løland's screen model. The agreement was good.

Further validation of the model should be performed, particularly on flexible net cages.

5 ACKNOWLEDGEMENT

This work has been carried out at the Centre for Autonomous Marine Operations and Systems (NTNU AMOS) and the centre for Exposed Aquaculture Operations (EXPOSED). The Norwegian Research Council is acknowledged as the main sponsor of both NTNU AMOS and EXPOSED. This work was supported by the Research Council of Norway through the Centres of Excellence funding scheme, project number 223254 – NTNU AMOS, and through the the Centres for Research-based Innovation funding scheme, project number 237790 – EXPOSED.

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